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Constraining the ^{19}Ne(p,γ)^{20}Na Reaction Rate Using a Direct Measurement at DRAGON

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Abstract. A direct measurement of the ^{19}Ne$(p, \gamma)^{20}$Na reaction has been performed in inverse kinematics at the DRAGON recoil separator, at an energy ~ 10 keV higher than previous measurements. The key resonance in the ^{19}Ne $+p$ system relevant for ONe novae and Type-I X-ray burst temperatures have been successfully measured for the first time. Preliminary estimates of the resonance energy and strength are reported as $E_{c.m.} \approx 458$ keV and $\omega\gamma \approx 18$ meV. These results are consistent with previous direct measurements, but disagree with the most recent study of the ^{19}Ne$(p, \gamma)^{20}$Na reaction rate. These preliminary results will be finalised after a forthcoming negative log-likelihood analysis.

Classical novae and X-ray bursts are among the most common types of explosive stellar phenomena observed in our Galaxy. These cataclysmic binary systems are stellar environments with high temperatures and densities, thought to be active regions of ongoing nucleosynthesis which energetically impact the surrounding interstellar medium (ISM).

Classical novae are binary systems where hydrogen-rich material is accreted from a main sequence or red giant branch star onto the surface of a companion white dwarf. As the accreted material mixes with the heavier elements already present on the surface of the white dwarf, a thermonuclear runaway is triggered, which leads to explosive mass ejections from the white dwarf's surface, with the process recurring over a time-scale of ~ 10^4 - 10^5 years [1]. The composition of the white dwarf star has a significant impact on the composition of the nova ejecta; novae with more massive oxygen-neon (ONe) white dwarfs are characterised by higher peak temperatures (~ 0.4 GK) than less massive carbon-oxygen (CO) white dwarfs (~ 0.2 GK), and are thus thought to synthesise elements up to the Si-Ca mass region [2]. Therefore, determining the nature of the underlying white dwarf is crucial to meaningfully compare theoretical calculations with astronomical data.

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Highly ionized fluorine lines have been observed in the optical spectra of Nova Mon 2012 [3], the detection of which is thought to be one of only four isotopic signatures from novae that could indicate a high-mass underlying ONe white dwarf [4]. In explosive stellar phenomena, ^{19}F is produced through the $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}(\beta^+)^{19}\mathrm{F}$ reaction sequence. However, this process can be bypassed at the high peak temperatures in ONe novae via the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}(\beta^+)^{19}\mathrm{Ne}$ reaction sequence. A nova nucleosynthesis sensitivity study by Iliadis et al. [5] has shown variations of a factor of 100 in the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction rate can change the final abundance of ^{19}F by up to a factor of 7. Therefore, the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction rate must be constrained to understand astronomical data from ONe novae.

X-ray bursts are cataclysmic binary systems similar to novae, but with a neutron star in place of the white dwarf. This results in much higher peak temperatures (~ 1.5 GK) and a much reduced burst recurrence time. Between outbursts, Type-I X-ray bursts produce energy via the β-limited hot CNO cycles. However, due to the higher peak temperatures achieved in X-ray bursts, during an outburst it becomes energetically feasible to “breakout” into the $rp-$process; a series of sequential, rapid proton capture reactions which has been suggested to synthesise elements up to the Sn-Te mass range[6]. The reaction sequence thought to dominate breakout into the $rp-$process is $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$, thus the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction is thought to be an important factor in understanding the behaviour of Type-I X-ray bursts. Moreover, it is thought that the strength of this reaction sequence helps to determine both the conditions for ignition to occur, as well as the burst recurrence time[7].

In the temperature range relevant for ONe novae and Type-I X-ray bursts, the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction is thought to be dominated by the contribution of a single, low-lying resonance located ~450 keV above the proton-emission threshold energy in ^{20}Na; equivalent to an excited state energy of $E_x = \sim 2650$ keV. However, for over twenty years, the exact strength and energy of this resonance state have been a subject of intense debate [8-21].

Previous direct measurements of the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction have utilised radioactive beams of ^{19}Ne [12-16], but none of these studies have identified the resonance of interest or measured its strength. Consequently, these studies have only been able to report upper limits of 18 meV[14], 21 meV[15], and 15 meV[16] for the resonance strength of the state of interest. Additionally, Page et al. [14], concluded that the dominant remaining uncertainty in the rate was the unknown spin-parity assignment of the state of interest, which had been given conflicting 1^+[8] and 3^+[9] assignments. However, the recent non-observation of the resonant state in a β-delayed proton study of ^{20}Mg, which would otherwise be highly populated by an allowed Gamow-Teller transition if the state had $J^\pi = 1^+$, strongly indicates that the state has spin-parity 3^+[20]. Moreover, the same study re-examined data from a previous high precision (^{3}He,t) study[10] in conjunction with the most recent, precise ^{20}Na proton threshold energy[17] to infer a more precise energy for the resonance of interest of $E_{c.m.} = 457(3)$ keV. Interestingly, a theoretical study by Fortune et al. derived a lower limit on the resonance strength, assuming a spin-parity assignment of 3^+, of 16-18 meV[18]; extremely close to the upper limits set by direct measurements.

The most recent study of the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction rate was performed by Belarge et al.[21]. A radioactive ion beam (RIB) of ^{19}Ne was used to populate states above the proton-emission threshold in ^{20}Na via a (d,n) reaction. The key resonance in the $^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ reaction was found to decay via strong proton decay branches at 440 keV and 200 keV, to the ground and first excited states. An angular distribution analysis of the decay to the first excited state found the resonant state of interest to have a spin-parity of 3^+, in agreement with Ref. [20]. Proton partial widths for both decays were determined from a couple-channel Born approximation. These were used, with a γ-ray partial width determined from the life-time of a proposed mirror state in ^{20}F at 2966.11(3) keV[22], to determine resonance strengths of proton captures to the ground and first excited state of $69^{\pm 15_{stat.}}_{\pm 17_{sys.}}$ meV and $21^{\pm 5_{stat.}}_{\pm 6_{sys.}}$ meV. These values of the resonance strength, contradict every previous direct measurement

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[14-16] and the reported resonance energy is inconsistent with previous indirect studies [12,21]. Consequently, the increase in resonance strength and decrease in resonance energy reported in Ref [21] leads to a ^{19}Ne$(p,\gamma)^{20}$Na reaction rate that is a factor ~20 higher than previous evaluations [5,10].

The subject of the present work is a new direct experimental study of the ^{19}Ne$(p,\gamma)^{20}$Na reaction performed ~10 keV higher in energy than previous direct measurements. An intense RIB of ^{19}Ne was used to measure the energy and strength of the key resonance in the ^{19}Ne+p system at ONe novae and X-ray burst temperatures for the first time. The experiment was performed at the DRAGON recoil separator[23], at the ISAC-I radioactive beam facility at TRIUMF. An intense RIB of ^{19}Ne^{1+} was produced by bombarding a SiC target with a primary beam of 500 MeV protons. Mass ~19 a.m.u. products were extracted, ionized in a FEIBAD ion source[24] and filtered by a high-resolution mass spectrometer. This beam was then initially accelerated up to 150 A·keV using a radio-frequency quadrupole (RFQ) accelerator and stripped to a 5$^+$ charge state using a thin carbon foil. The ^{19}Ne^{5+} beam was then accelerated to an energy of 9.24 MeV and impinged upon a windowless gas target of H_2 at a pressure of 5 Torr for 89 hours. The incoming beam energy and gas target pressure were chosen to cover a center-of-mass energy range of E_{cm} = 447 − 465 keV across the gas target volume. Surrounding the windowless gas target is a highly efficient array of bismuth germanate (BGO) detectors[23], used to detect the radiative capture γ-rays while ^{20}Na^{6+} recoils were transmitted to the focal plane of DRAGON. These recoils were identified using both a local time-of-flight (TOF) system, consisting of two micro-channel plates (MCPs) detecting secondary electron emission from thin Diamond-like Carbon (DLC) foils, and an ionization chamber filled with isobutane gas. These particles could be easily distinguished from scattered and/or charge-changed ("leaky") beam through use of a dual TOF technique[25].

The gas target stopping power was determined using measurements with gas in/out of the target system at the nominal beam energy used during the experiment, and the charge state distribution for the recoils of interest was measured using a stable beam of ^{23}Na. Determining the number of incoming beam particles was achieved by measuring β decays in two 6mm thick plastic scintillators located part-way through DRAGON, where the 6$^+$ component of the unreacted beam was stopped. The average ^{19}Ne beam intensity over 89 hours was found to be ~ 7 x 10^6 pps, amounting to a total integrated beam flux of ~2.4 x 10^{12}. It should be noted that the isobaric beam contaminant ^{19}F was also present at a level of ~ 2 x 10^7 pps, but that reactions involving ^{19}F could be easily distinguished from those involving ^{19}Ne using the ionization chamber.

Figure 1 shows the γ-gated MCP TOF vs separator TOF spectrum obtained for the incident beam energy E_{beam} = 486 A·keV. A distinct cluster of 15 events, free from background, indicate the presence of an A = 20 radiative capture resonance. By additionally requiring the observation of a ^{20}Na event in the ionization chamber, a preliminary total of 9 "golden" ^{19}Ne +p recoil-γ coincidences is obtained, as shown in Figure 2. Moreover, it is clear from Fig. 2 that any events arising from the contaminant ^{19}F$(p,\gamma)^{20}$Ne reaction are easily separable from the ^{20}Na recoils of interest.

A key strength of using the DRAGON recoil separator to study astrophysical resonant reaction rates is that it provides an independent measurement of the resonance strength - from the yield of detected recoils at the focal plane detectors - and the resonance energy - from the spatial distribution along the beam axis of the detected radiative capture γ-rays in the BGO array surrounding the gas target. This is of particular importance in the current study, where both the resonance strength and the resonance energy are not well defined. However, a determination of the resonance energy in the current study was made more complicated due to the low number of detected recoil-γ coincidences. Consequently, the position along the beam axis where the mean number of radiative capture γ-rays were detected is not very accurately constrained.

However, it was still possible to extract a preliminary value of the resonance energy by using the arithmetic mean position along the beam axis where the radiative capture γ-rays were detected.

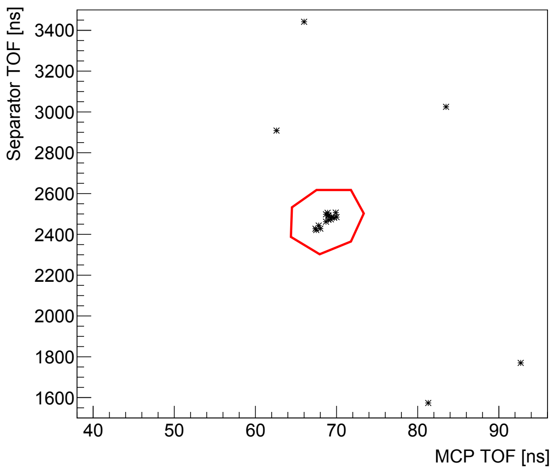

Figure 1. Dual TOF spectrum showing MCP TOF vs TOF through the DRAGON recoil separator. The red polygon indicates the expected location of A = 20 recoils.

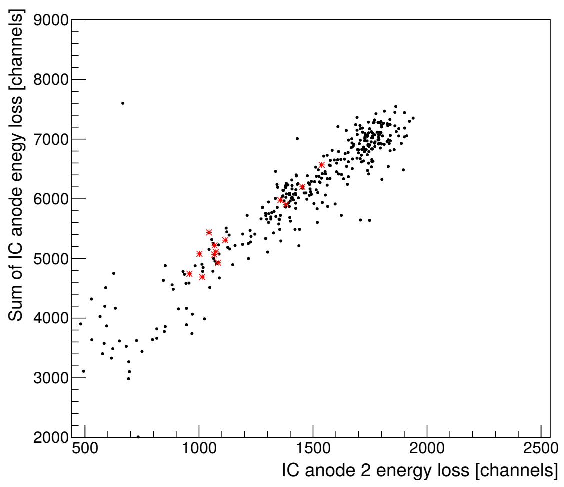

Figure 2. Total energy loss in the ionization chamber vs energy loss in the second anode of the ionization chamber. Black dots indicate singles events observed from all production runs. Red stars indicate events within the red polygon in Figure 1.These events appear to take up two main regions; one, around the center of the Figure, corresponding to contaminant ^{19}F$(p,\gamma)^{20}$Ne reactions; and the other, to the south-west of the center of the Figure, corresponding to the ^{19}Ne$(p,\gamma)^{20}$Na reactions of interest.

Converting this mean position to a resonance energy, using the methodology set out in Ref. [26], yields a preliminary resonance energy of ~458 keV. Using the thick target resonance strength formula [25], a preliminary estimate of the resonance strength of ~18 meV could also be determined.

In summary, we have performed a direct measurement of the ^{19}Ne$(p,\gamma)^{20}$Na reaction in inverse kinematics at the DRAGON recoil separator, at an energy ~ 10 keV higher than previous direct measurements. The key resonance in the ^{19}Ne $+p$ system at ONe novae and Type-I X-ray burst temperatures has been successfully measured for the first time. Preliminary estimates of the resonance energy and strength are $E_{c.m.} \approx 458$ keV and $\omega\gamma \approx 18$ meV, respectively. These results are in stark contrast with the most recent study of the ^{19}Ne$(p,\gamma)^{20}$Na reaction rate [21], but are more consistent with the upper limits from historical direct measurements. Of particular note, the preliminary resonance energy is in good agreement with that inferred in the study by Wallace et al. [20]. Going forward, a negative log-likelihood analysis[27] will be performed to constrain the resonance strength and energy from this study more precisely. Furthermore, it would be of interest to check the impact of the final updated resonance energy and strength on the nucleosynthesis of both novae and X-ray bursts through the use of hydrodynamic simulations.

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